Accessing gluon Sivers at EIC

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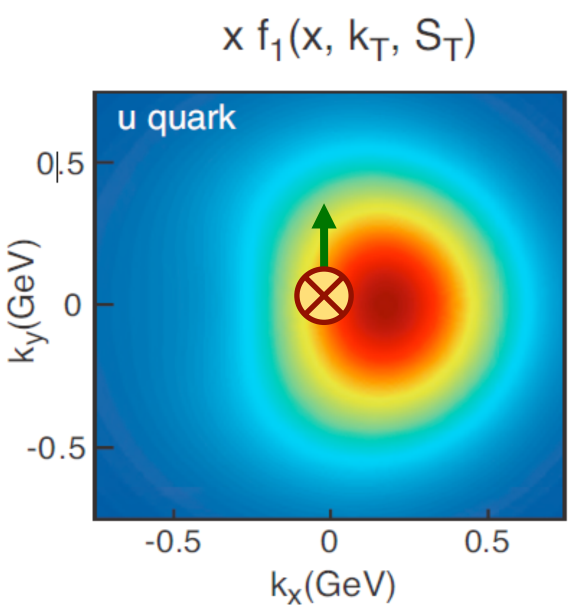
Nucleon Landscape

- Nucleon is a dynamical system of quarks and gluons
  - How partons are distributed in space and momentum inside the nucleon?
  - How are these **quark and gluon distributions correlated** with the over all nucleon properties, such as **spin** direction?
  - Spin as fundamental intrinsic property and also as a mechanism to do tomography of many body system of quarks and gluons
- EIC: polarized collider to have full access to the nucleon dynamics

3D imaging of partonic structure of nucleon

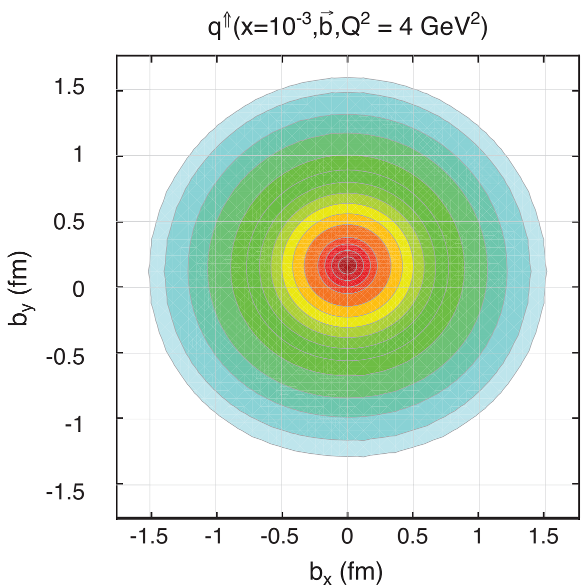
Transverse Momentum Dependent parton distributions (TMDs)

- confined motion in a nucleon (semi-inclusive DIS)
- 2+1D picture in momentum space (k_T)



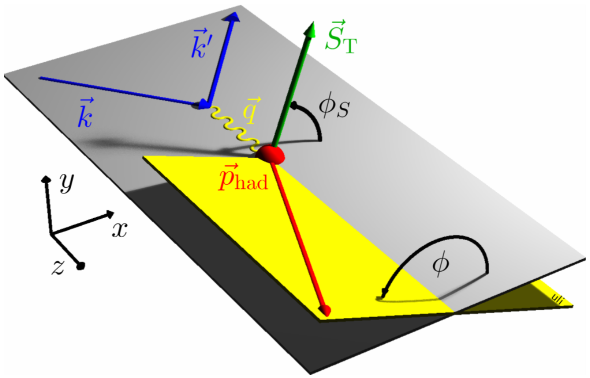
Generalized Parton Distributions (GPDs)

- Spatial imaging of quarks and gluons (exclusive DIS)
- 2+1D picture in impact parameter space (b)

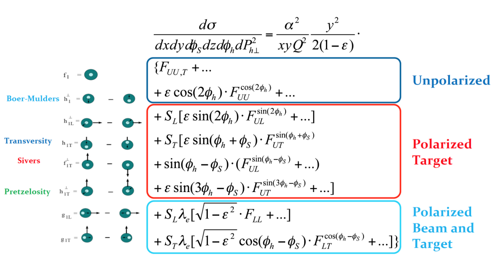


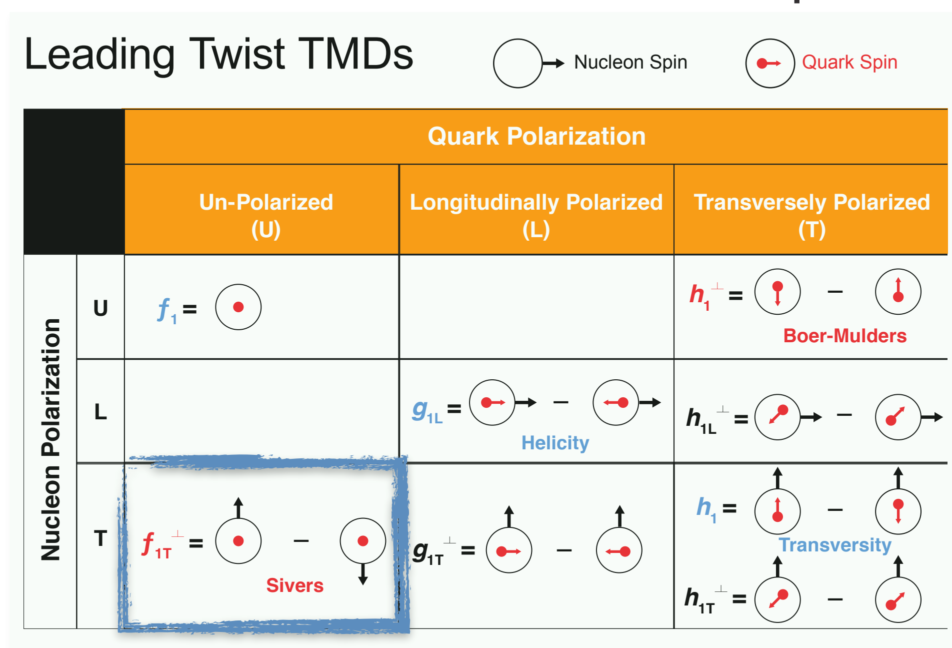
Transverse Momentum Dependent PDFs

observable: azimuthal modulations of 6-fold differential SIDIS cross section $\frac{d\sigma}{dx dQ^2 dz d\phi_s d\phi_h dp_T^h}$



- multi-scale process: Q^2, p_T
- TMD framework/factorization applicable for $Q^2 >> p_T$
- so far only valence quark TMDs extracted from fixed target data
- **very different evolution then collinear PDFs:** pertubative & **non-pertubative** contributions
- different TMDs can be defined and probed in SIDIS





Similar for gluons

Sivers Function

Correlation of nucleon's transverse spin with k_T of an unpolarized quark/gluon: Can be viewed as partonic motion inside nucleon

$$f_{q/P^\uparrow}(x,\mathbf{k}_\perp,S) = f_1(x,\mathbf{k}_\perp^2) - \frac{\mathbf{S}\cdot(\hat{\mathbf{P}}\times\mathbf{k}_\perp)}{M} f_{1T}^\perp(x,\mathbf{k}_\perp^2)$$: $\sin(\Phi_h - \Phi_S)$ modulation

unpolarized TMD

important link to physics of gluon saturation at small x

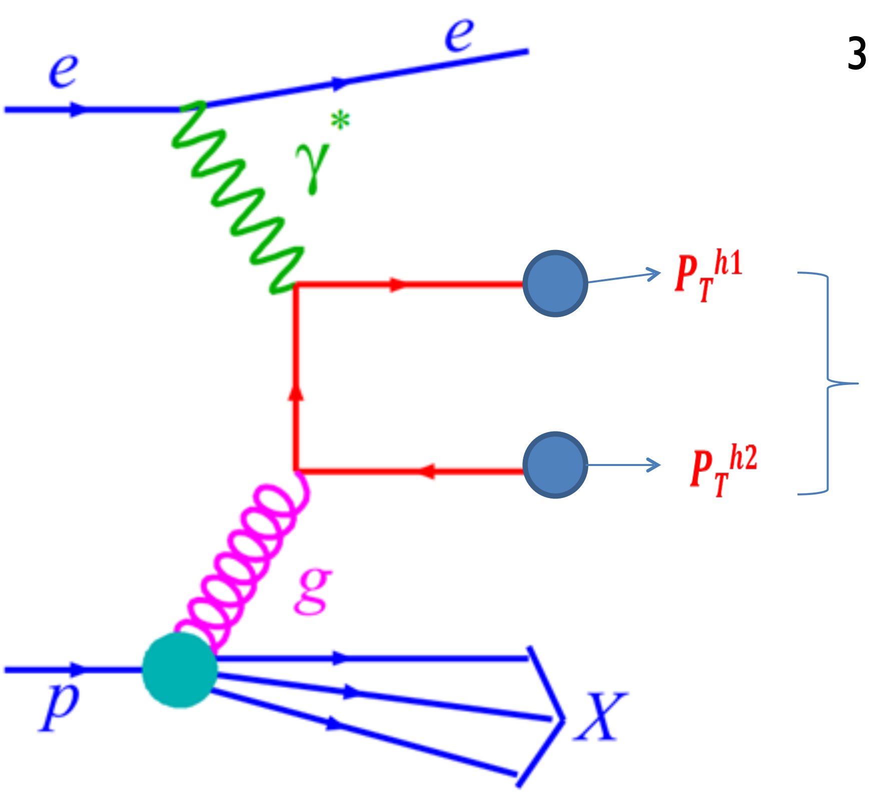
Sivers function

- "dipole" deformation
- measures spin-orbit correlations
- link to parton orbital motion (through models)
- reveals non-trivial aspects of QCD color gauge invariance

Due to the different gauge links involved in the processes, the gluon Sivers effect extracted from EIC would be an independent gluon Sivers function distinct from that obtained in pp collisions and can hardly be accessed in other collisions.
Gluon Sivers studies at an EIC will provide a unique test of the fundamental non-perturbative QCD effects and provide complementary information.

Accessing gluon dynamics in DIS

Photon-Gluon Fusion (PGF)



1. Tag photon-gluon fusion events
2. Find back-to-back hadron pairs from the quark-antiquark jet
3. Reconstruct the gluon dynamics with the hadron/jet pair information

Gluon information can be extracted with the hadron/jet pairs from the quark-antiquark jet.

Back-to-back limit:

$P_T' = |\mathbf{P}_T^{h1} - \mathbf{P}_T^{h2}|/2$

$k_T' = |\mathbf{P}_T^{h1} + \mathbf{P}_T^{h2}|$

$k_T' << P_T'$

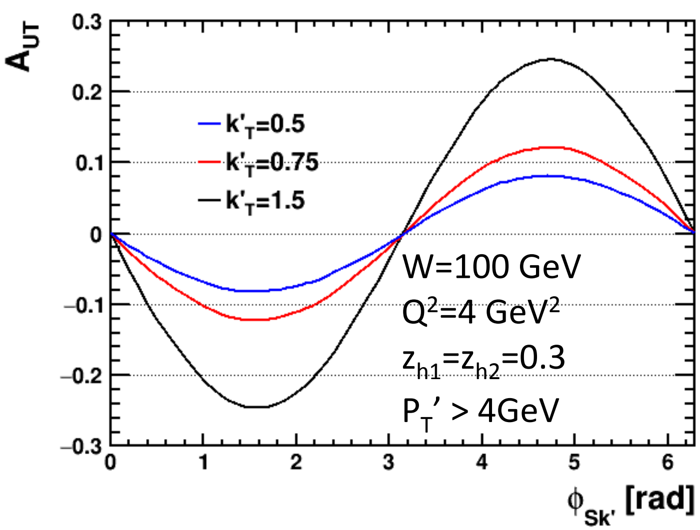
Theoretical framework for the model calculation for Sivers function

$$\frac{d\sigma_{\text{tot}}^{\gamma^*+p^\uparrow\to h_1+h_2+X}}{dz_{h1}dz_{h2}d^2p_{h1\perp}d^2p_{h2\perp}} = C\int_{z_{h1}}^{1-z_{h2}}\sum_q dz_q \frac{z_q(1-z_q)}{z_{h2}^2 z_{h1}^2} d^2p_{1\perp}d^2p_{2\perp}\hat{f}_{g/p^\uparrow}(x_g,k_\perp)$$
$$\times\,\mathcal{H}_{\text{tot}}^{\gamma^* g\to q\bar{q}}(z_q,k_{1\perp},k_{2\perp})e_q^2 D_{h1/q}\left(\frac{z_{h1}}{z_q},p_{1\perp}\right)D_{h2/\bar{q}}\left(\frac{z_{h2}}{1-z_q},p_{2\perp}\right)$$

$$\hat{f}_{a/p^\uparrow}(x,k_\perp) = f_{a/p}(x,k_\perp) - f_{1T}^{\perp a}(x,k_\perp)\frac{\vec{S}\cdot(\hat{\vec{P}}\times\vec{k}_\perp)}{M_p}$$

$$A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \frac{\Delta^N f_{g/p^\uparrow}(x,k_\perp)}{2f_{g/p}(x,k_\perp)}$$

$$\Delta^N f_{a/p^\uparrow}(x,k_\perp) = -\frac{2k_\perp}{M_p}f_{1T}^{\perp a}(x,k_\perp)$$



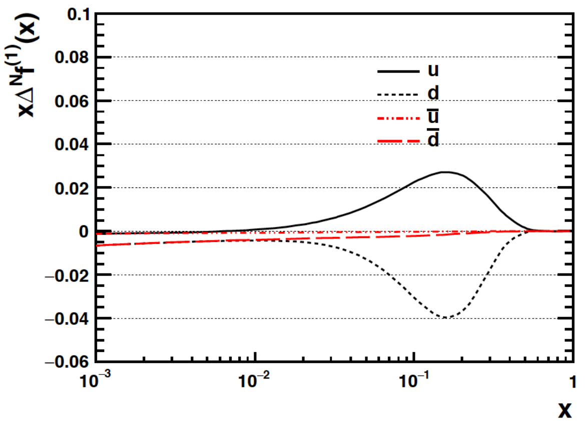
- Negative gluon Sivers saturating the positivity bound is assumed.
- Stronger asymmetry size observed for larger k_T'.

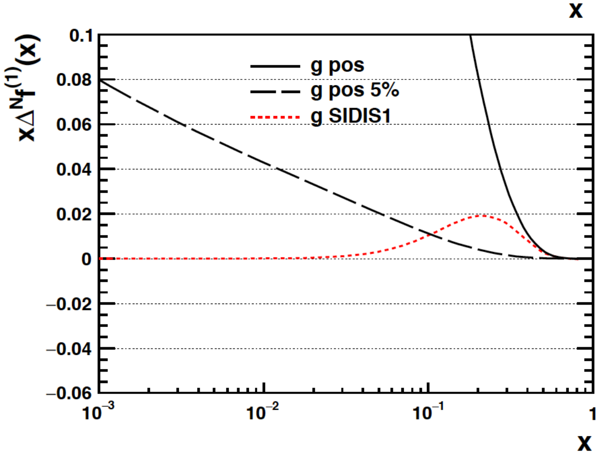
$$\phi_{Sk'} = \phi_S - \phi_{k'_T}$$

Inputs to the model calculation

Quark Sivers: JHEP 04 (2017) 046 Anselmino et al.

Gluon Sivers: JHEP 09 (2015) 119 D'Alesio et al.
u,d + Kretzer FF (SIDIS1)





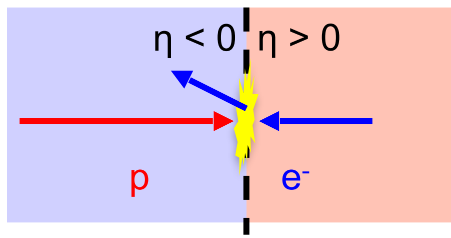
Positivity bound ansatz:

$$f_{1T}^{\perp g} = -\frac{2\sigma M_p}{k_\perp^2 + \sigma^2} f_g(x, k_\perp), \quad \sigma = 0.8$$

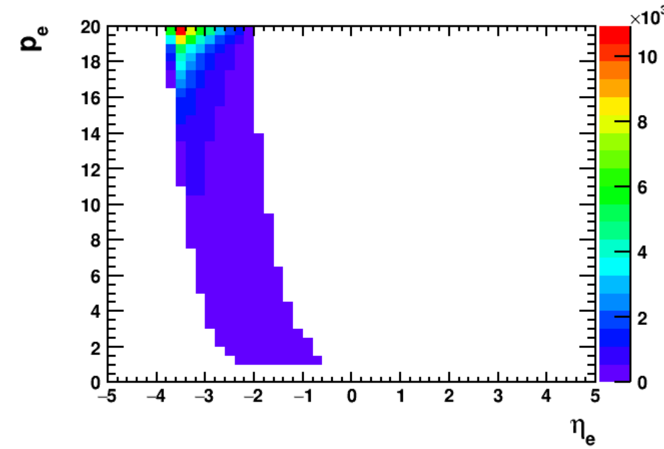
- Quark Sivers with only u and d contribution extracted from HERMES and COMPASS data.
- Gluon Sivers from a fit to RHIC π^0 A_N data.
- Fitted gluon Sivers is much smaller than quark Sivers in a wide range of x.

EIC setup for gluon SSA study

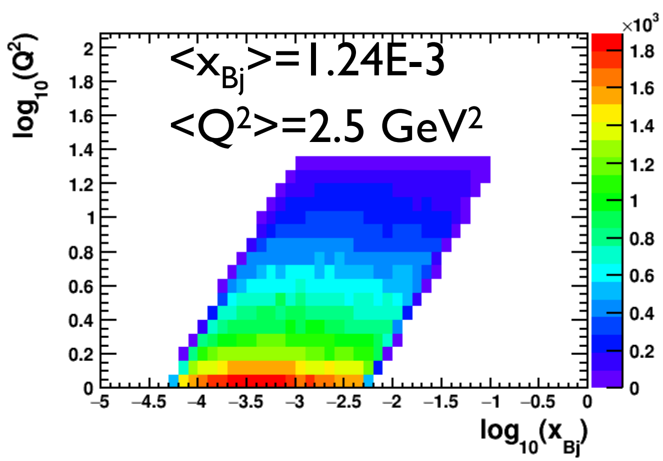
Kinematics:
$ep^{\uparrow}$ 20x250 GeV
$\sqrt{s}$=141 GeV
0.01<y<0.95
$1<Q^2<20$ GeV^2

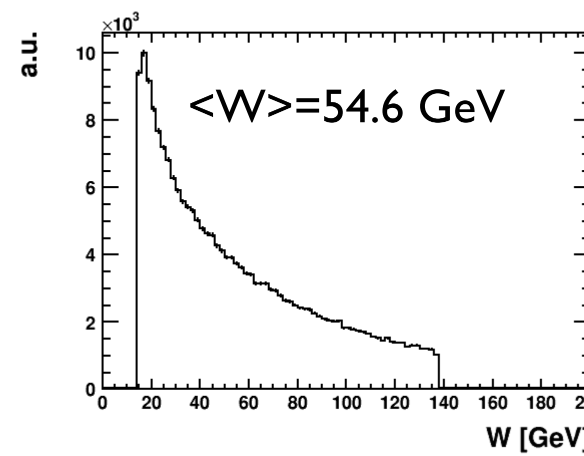


Scattered electron



Final state observables
1. D^0 pair (+single D^0)
2. Dihadron
3. Dijet
4. K^+K^- pair





D^0 selection

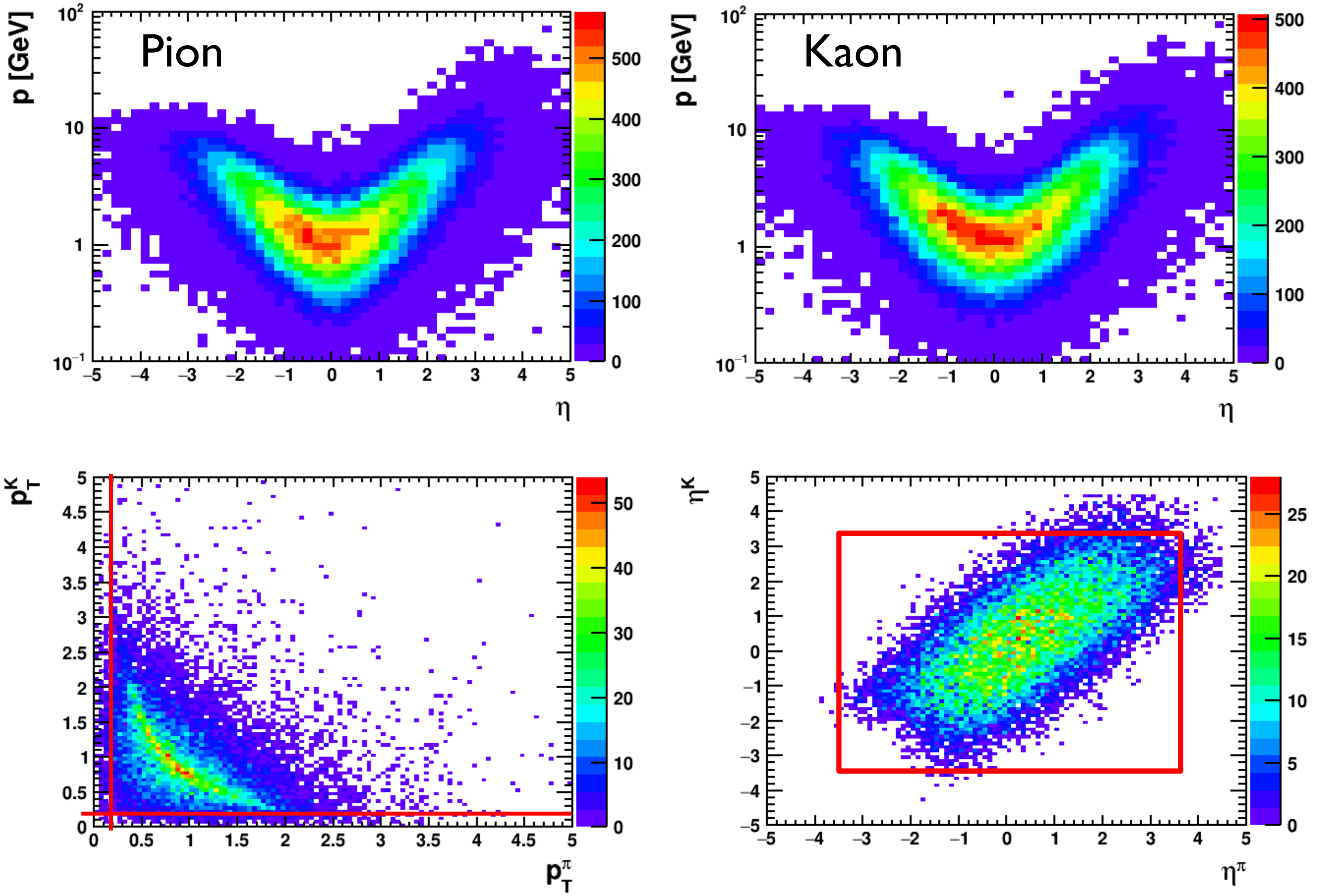
$$ep^{\uparrow} \rightarrow e'c\bar{c}X$$

$$D^0(c\bar{u}) \rightarrow \pi^+(u\bar{d})K^-(s\bar{u})$$

$$\bar{D}^0(\bar{c}u) \rightarrow \pi^-(\bar{u}d)K^+(u\bar{s})$$

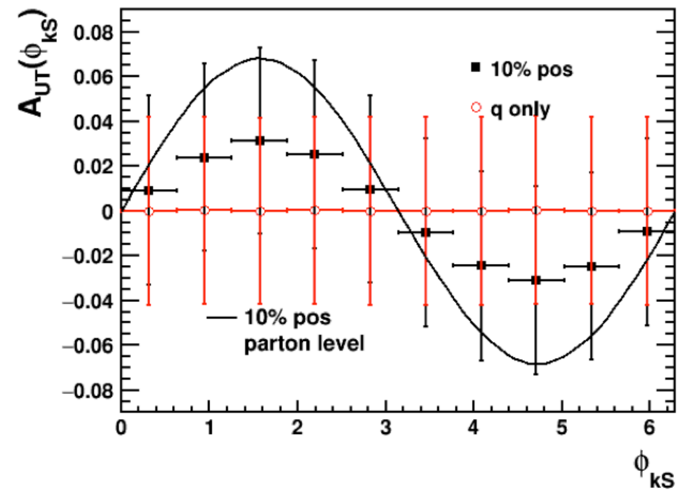
Branching ratio: 3.9%

- Acceptance for PID is assumed to be $|\eta| < 3.5$
- Decay products from D^0 mesons are mostly less than 10 GeV within $|\eta|<1$
- Decay products $p_T>0.2$ GeV (94% survival)

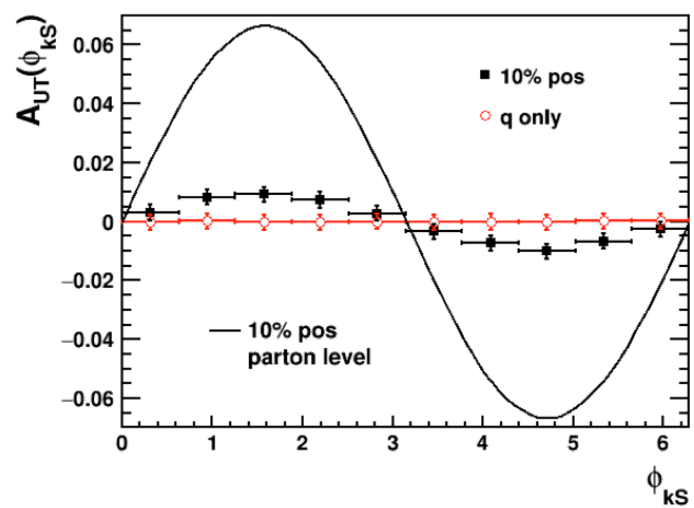


Projections for the SSA with D^0

$$ep^{\uparrow} \rightarrow e' c\bar{c}X$$



D^{0}D^{0}bar+X

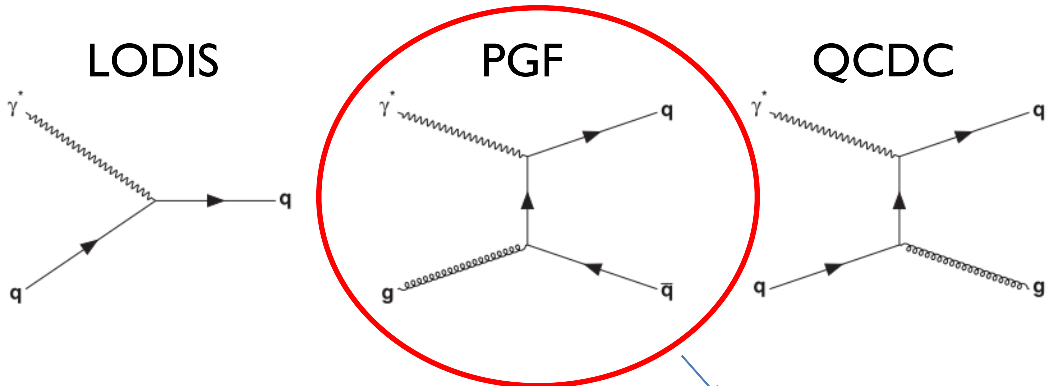


D^0+X

- ep 20x250 GeV
- $D^0 \rightarrow K\pi$ in acceptance
- $p_T > 0.2$ GeV, $z > 0.1$
- correlation limit: $k_T < 0.5 * P_T$
- $<x_g> \sim 0.03$
- $\sigma_{DDbar} = 2.7\text{x}10^{-3}$ nb
- Integrated luminosity 10 fb^{-1}: $\delta A_{UT} \sim 2\text{x}10^{-3}$, sensitive to a few % of positivity limit

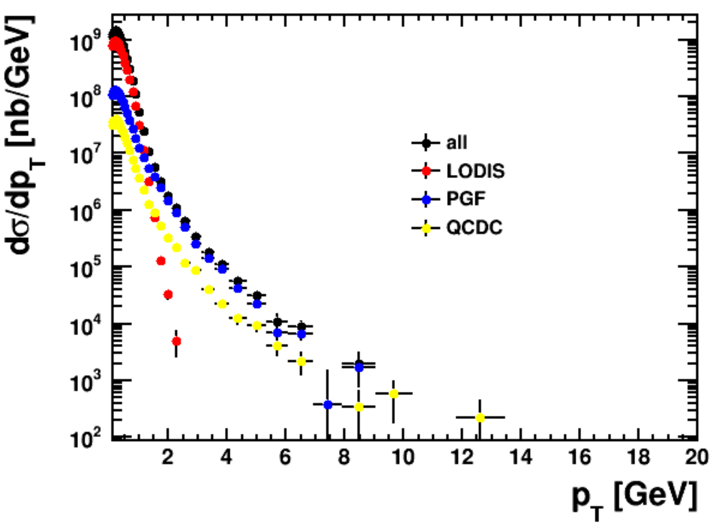
The statistical uncertainty obtained with P=70% polarization $(\delta A_{UT})^2 = \frac{1}{P^2 \sigma L}$

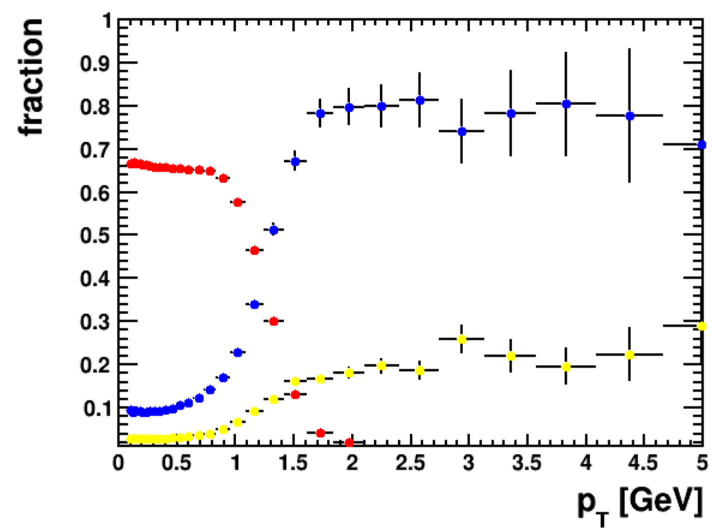
Dihadron in PGF



Signal

p_T>1.7 GeV effectively enhances the gluon initiated process.





Dihadron pair selection

Kinematic cuts:

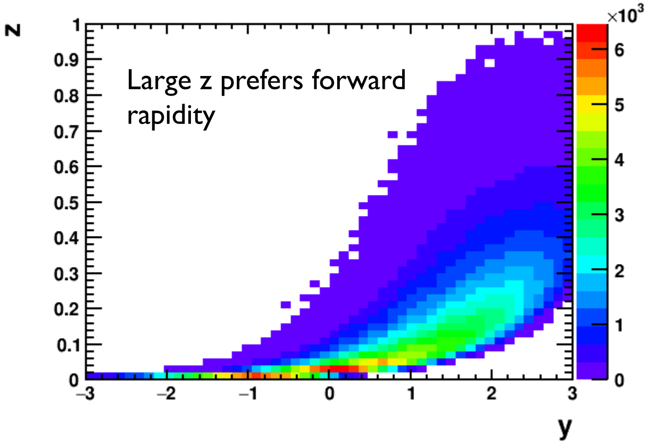
ep 20x250 GeV

$0.01<y<0.95$

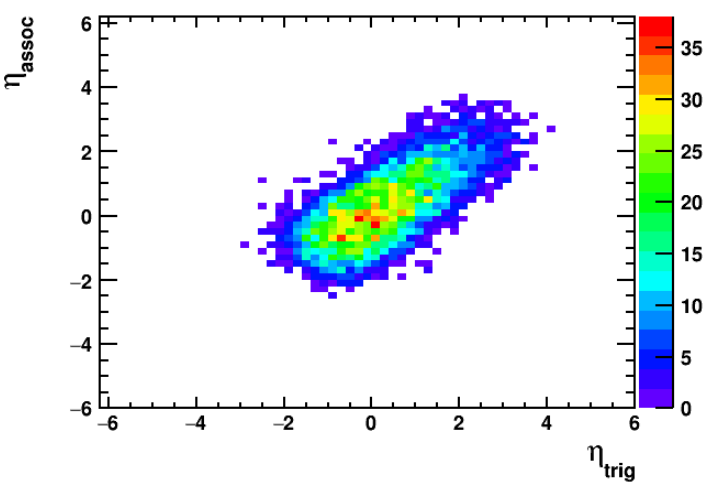
$1<Q^2<20$ GeV^2

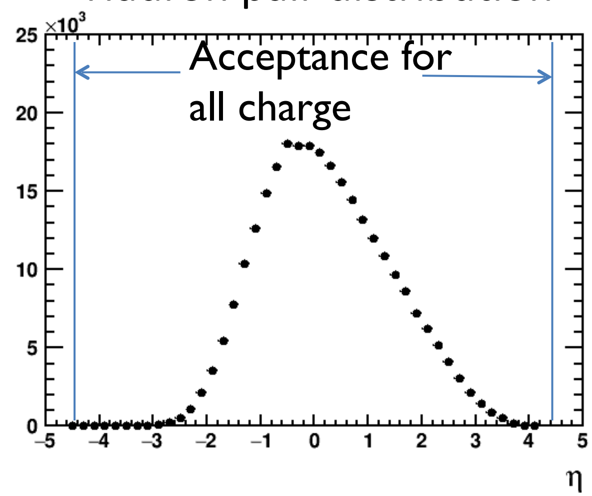
$p_T>1.7$ GeV, $z_h>0.1$, $|\eta|<4.5$

Back-to-back limit: $k_T' < 0.7P_T'$

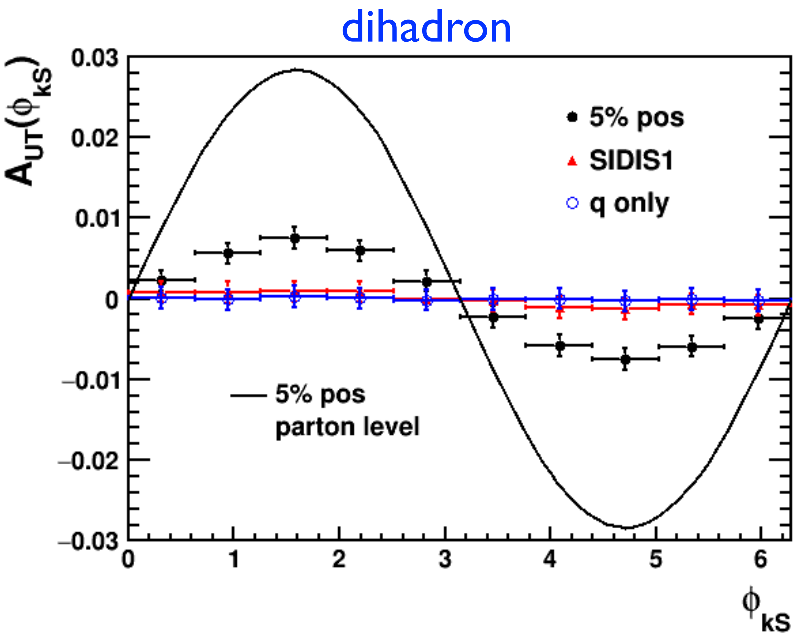


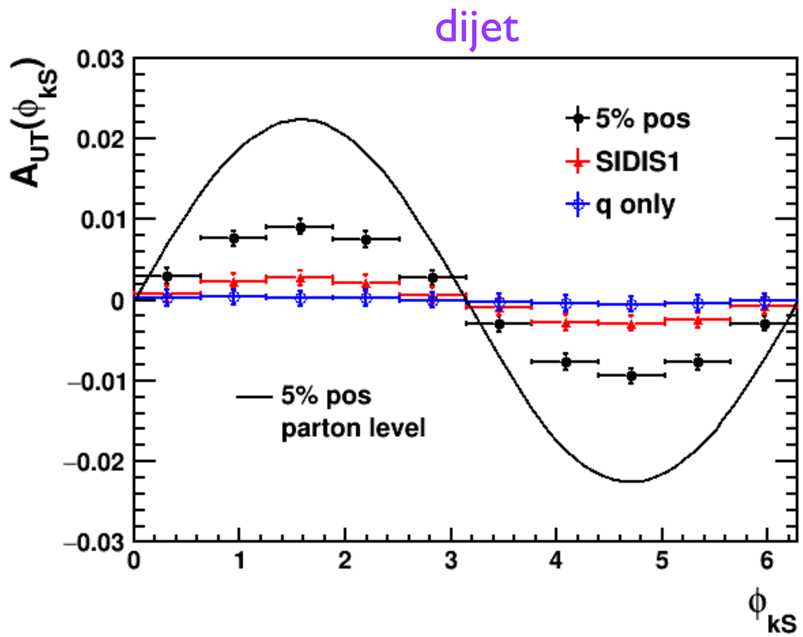
Hadron pair distribution





Projections on the SSA with Dihadron and Dijet





Kinematic cuts:

ep 20x250 GeV

$0.01<y<0.95$

$1<Q^2<20$ GeV^2

$|\eta|<4.5$

Dihadron: $p_T>1.7$ GeV, $z_h>0.1$

Dijet: $p_{Tjet1}>4.5$ GeV, $p_{Tjet2}>4$ GeV

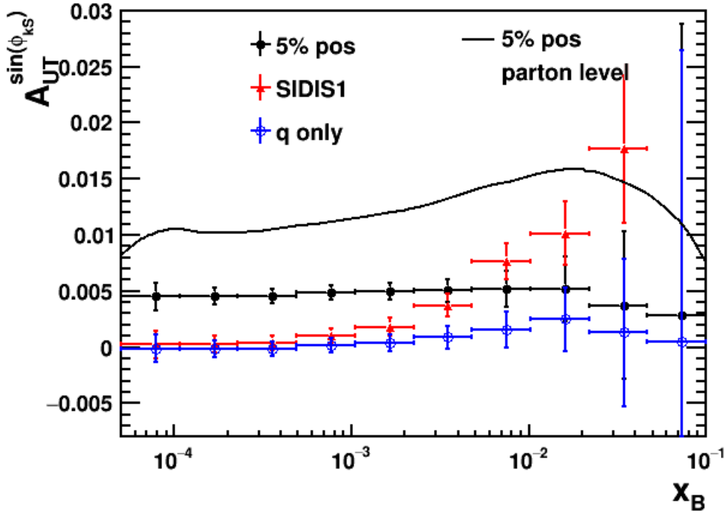
Back-to-back limit: $k_T' < 0.7P_T'$

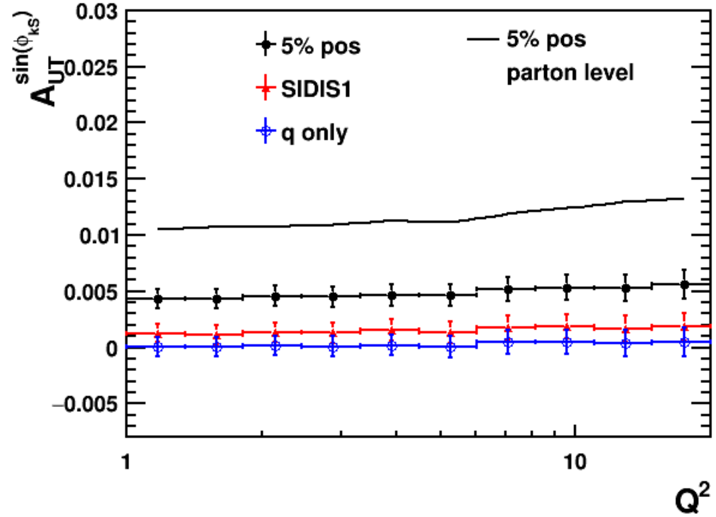
$\int L = 10$ fb^{-1}

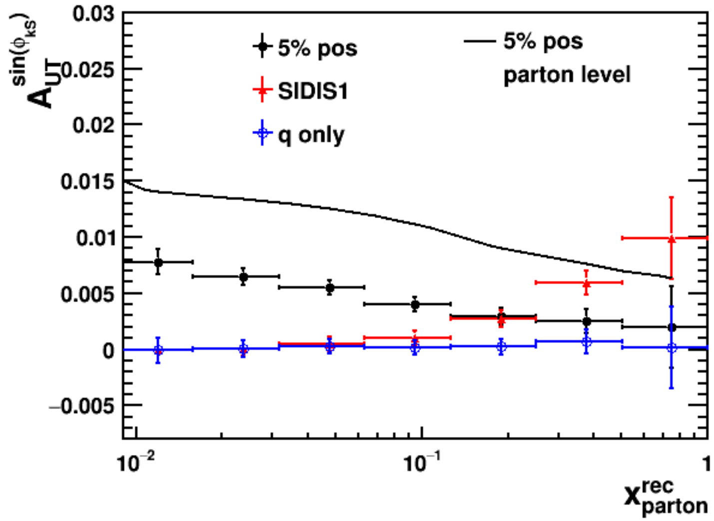
proton polarization=70%

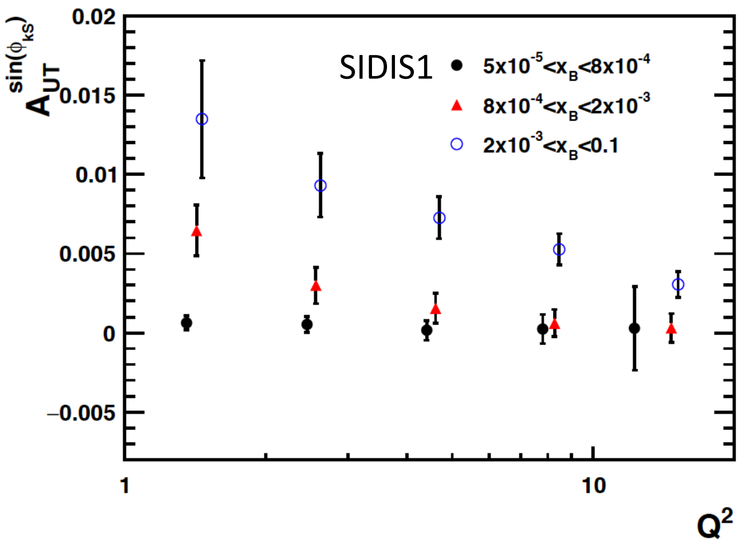
Jet @ EIC: B. Page's Talk

Gluon SSA with Dijet







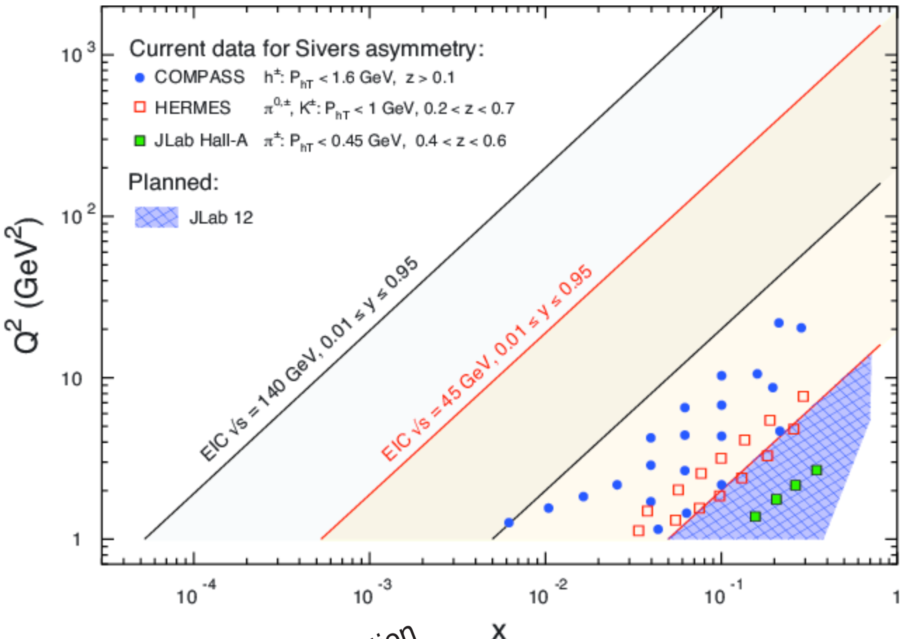


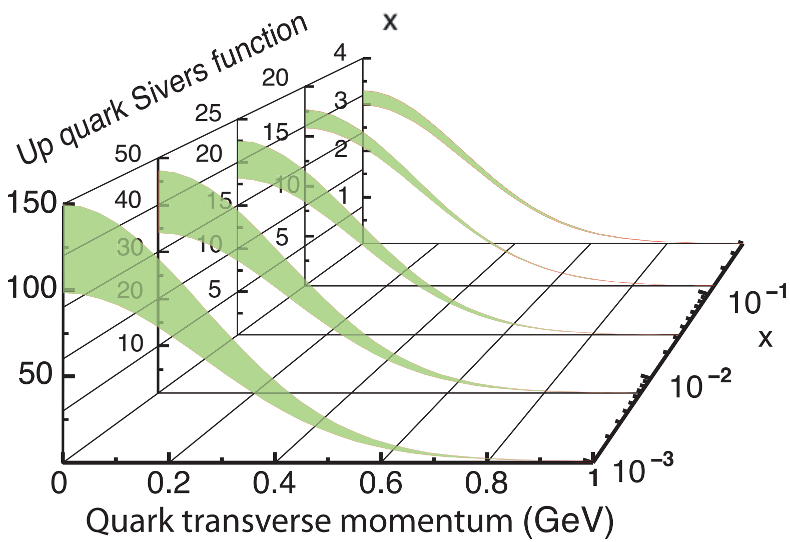
Summary

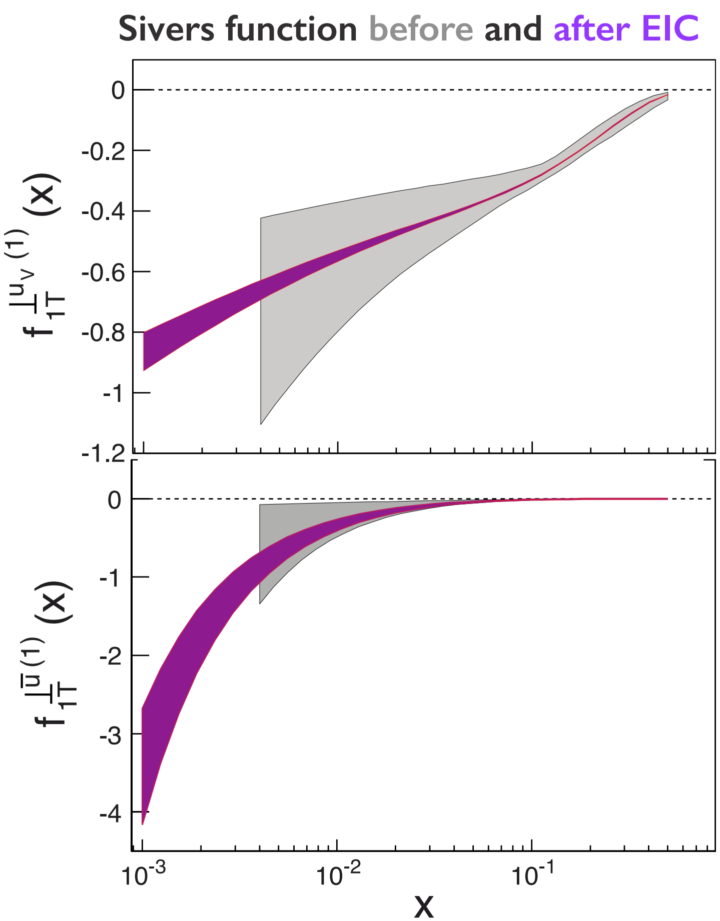
- Gluon TMDs is ingredient of complete 3D imaging of nucleon, and can be uniquely measured at EIC by measuring gluon Sivers function
- Gluon Sivers can be accessible and constrained in a wide kinematic range via photon-gluon coupling - D^0, dihadron, dijet within EIC's machine and detector reach


BACKUP

quark Sivers at EIC



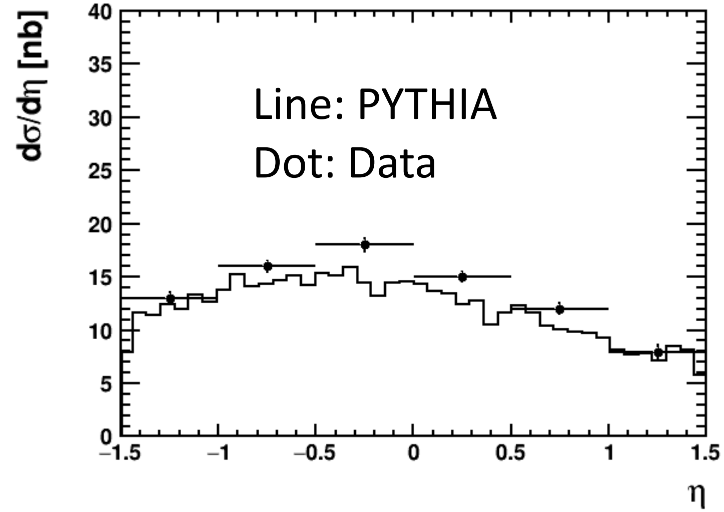


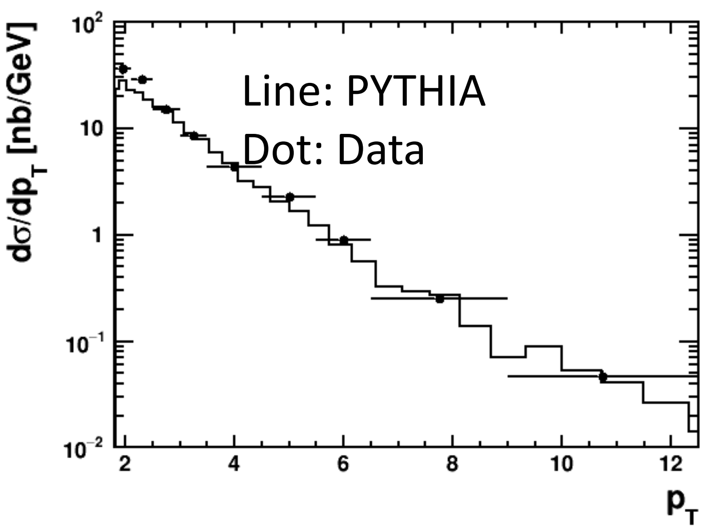


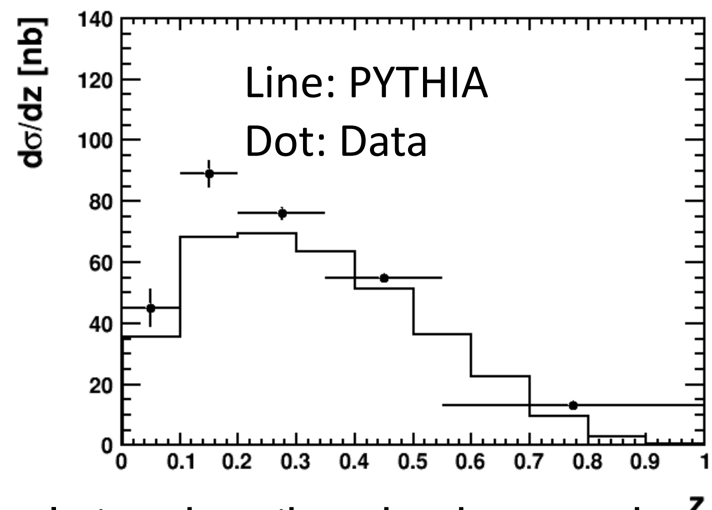
PYTHIA confronted with HERA data

Data taken from: EPJC 72, 1995 (2012)

Comparing with D* measurements from HERA
ep 27.6 GeV x 920 GeV
$Q^2<2$ GeV^2, $100<W<285$ GeV, $|\eta|<1.5$
p_T, η defined in gamma-hadron center of mass frame



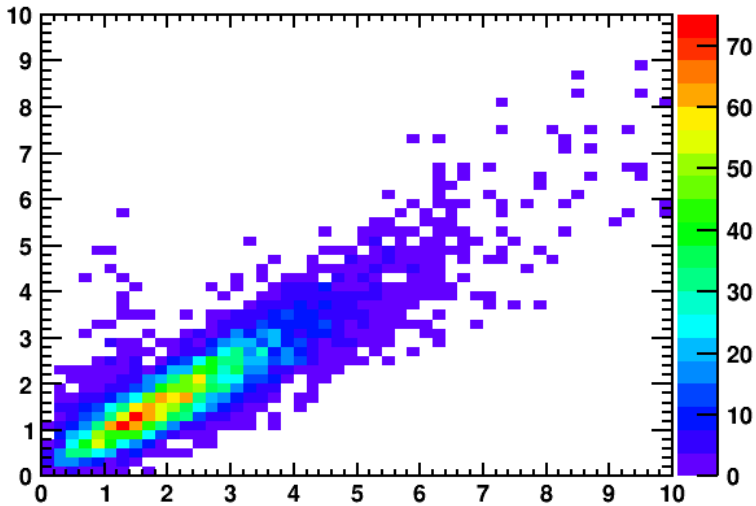




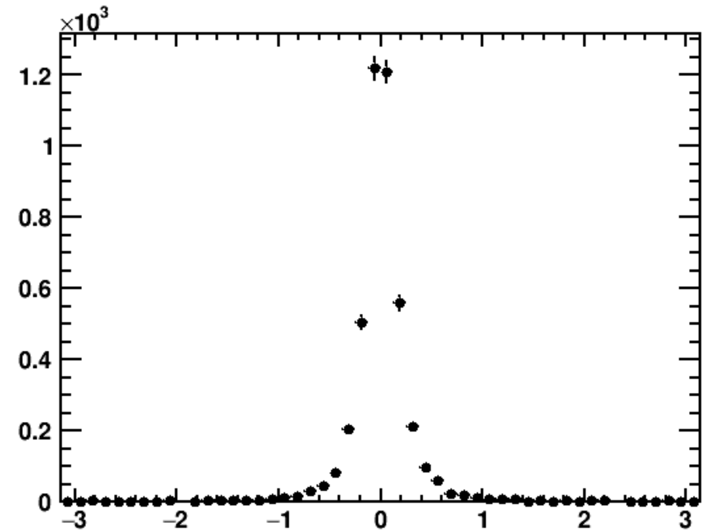
Simulation describes the data trend.

D^0 as c-quark proxy

$$ep^{\uparrow} \rightarrow e' c\bar{c}X$$



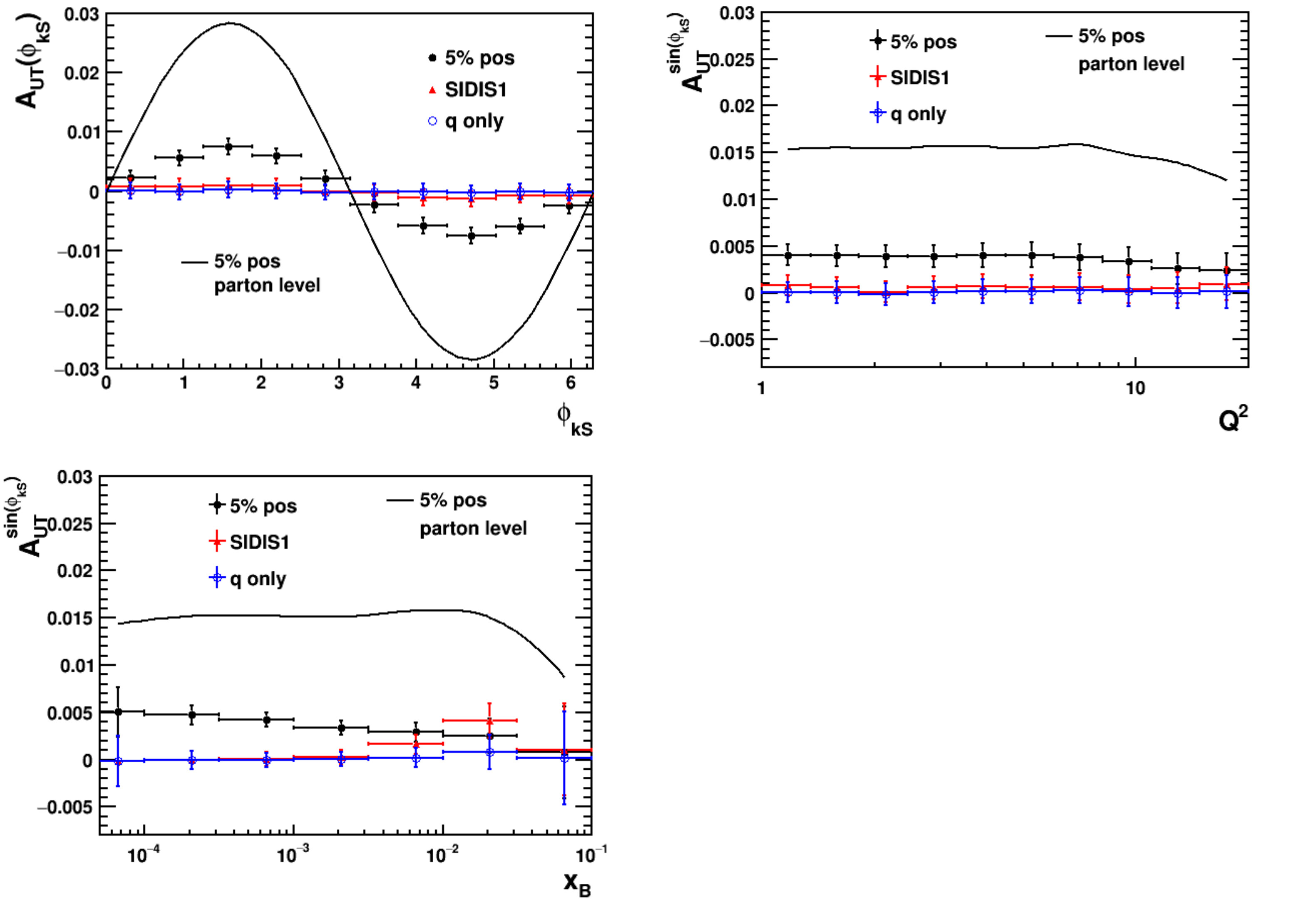
$p_{T\ D^0}$ vs $p_{T\ \text{c-quark}}$ (GeV)



$\Phi_{\text{c-quark}} - \Phi_{D^0}$

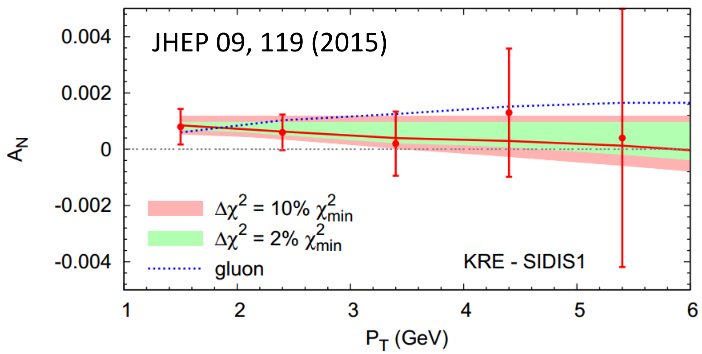
D^0 meson takes a large fraction of the charm quark energy, serves as a proxy to the c-quark information.

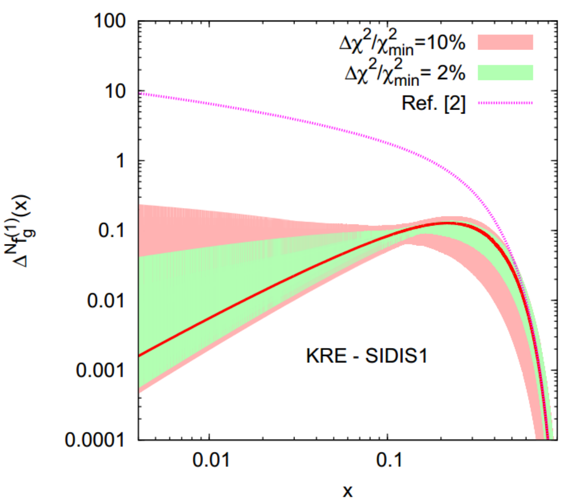
Gluon SSA with dihadron



Current constraints on gluon Sivers

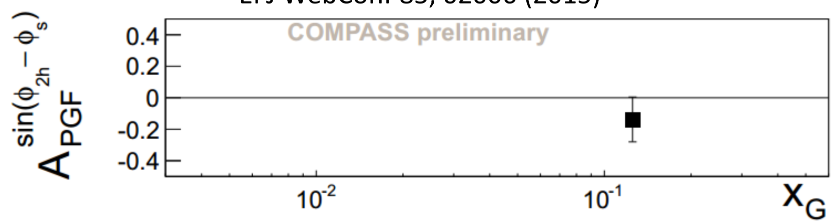
Extraction based on A_N data at RHIC (pi0)





Extraction on COMPASS data

EPJ WebConf 85, 02006 (2015)



$$\mathbf{A}_{\mathbf{PGF}}^{\sin(\phi_{2h}-\phi_S)} = \mathbf{-0.14 \pm 0.15(stat.)}$$

$$\langle x_G \rangle = 0.126$$

- Effective gluon Sivers from A_N may differ from the actual gluon Sivers in TMD.
- Limited x and Q^2 range explored in SIDIS. Still allow for gluon Sivers contributions of $1/N_c$.
- No hard constraints at this moment.

Extraction of quark Sivers

- Ansatz for transverse momentum and x dependence
- Sizable Sivers effect
- u, d quark Sivers with opposite sign

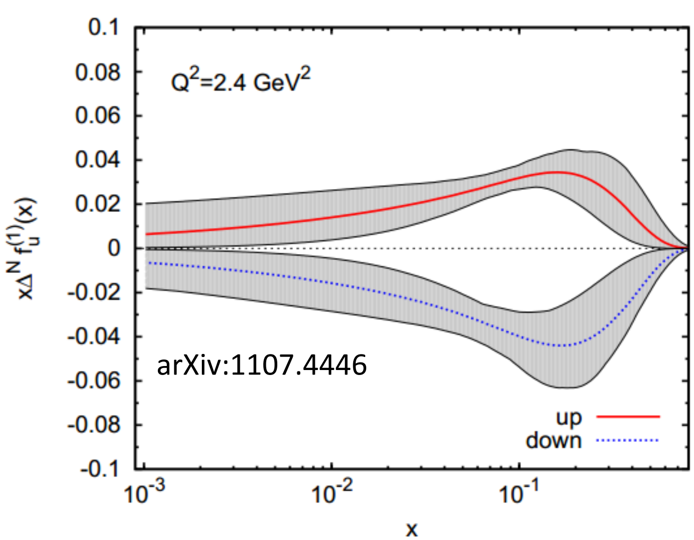
$$\hat{f}_{a/p^\uparrow}(x,k_\perp) = f_{a/p}(x,k_\perp) - f_{1T}^{\perp a}(x,k_\perp)\frac{\vec{S}\cdot(\hat{\vec{P}}\times\vec{k}_\perp)}{M_p}$$

$$\Delta^N f_{a/p^\uparrow}(x,k_\perp) = -\frac{2k_\perp}{M_p} f_{1T}^{\perp a}(x,k_\perp)$$

$$\Delta^N f_{a/p^\uparrow}(x,k_\perp) = 2\mathcal{N}_a(x) f_{a/p}(x,k_\perp) h(k_\perp)$$

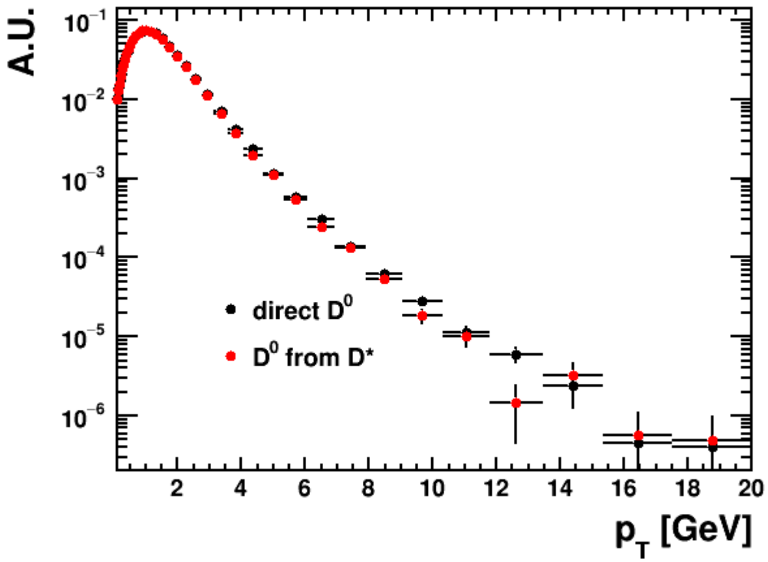
$$\mathcal{N}_a(x) = N_a x^{\alpha_a}(1-x)^{\beta_a}\frac{(\alpha_a+\beta_a)^{(\alpha_a+\beta_a)}}{\alpha_a^{\alpha_a}\beta_a^{\beta_a}}$$

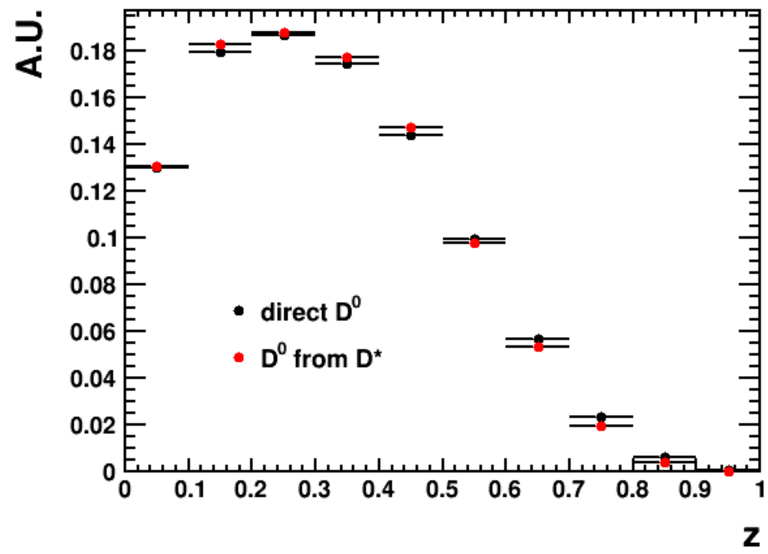
$$h(k_\perp) = \sqrt{2e}\,\frac{k_\perp}{M}\,e^{-k_\perp^2/M^2}$$



Barely known for the gluon Sivers!

D^0 feed-down from D*

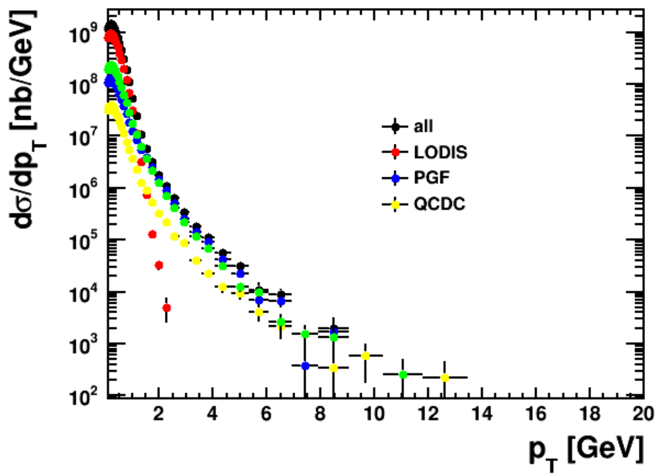


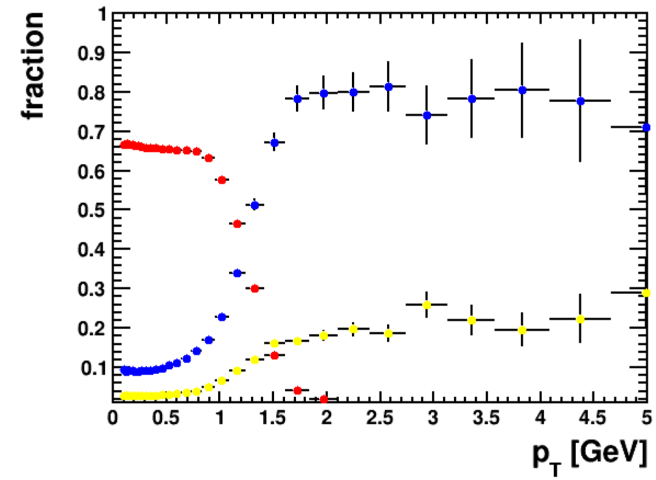


D^0 from D* decay similar to the directly generated D^0s, therefore all D^0s are analyzed.

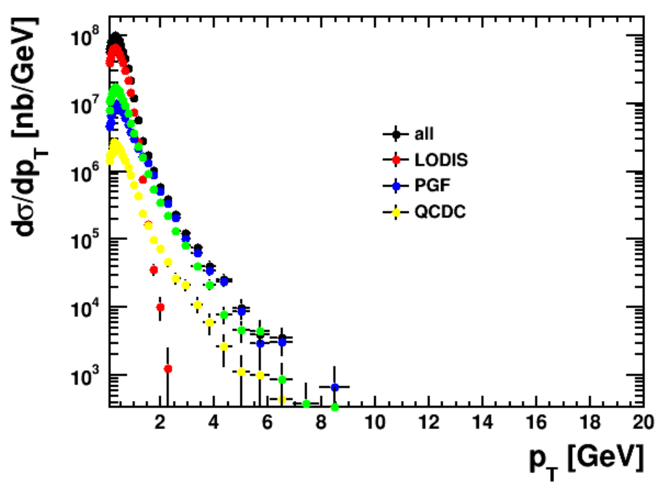
Charged hadron vs kaon spectrum

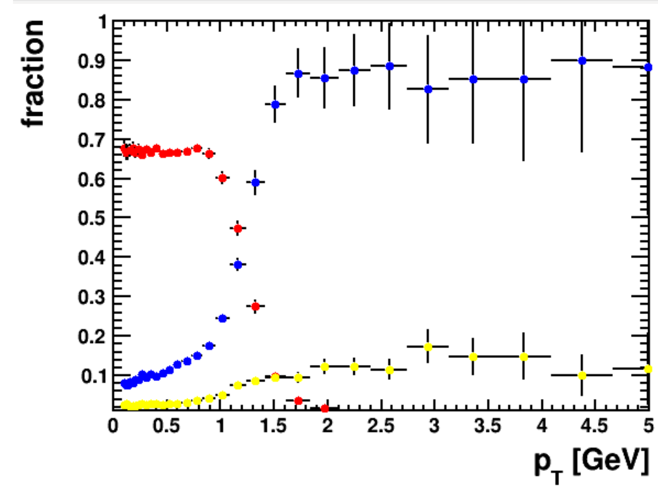
Charged hadron





Charged Kaon





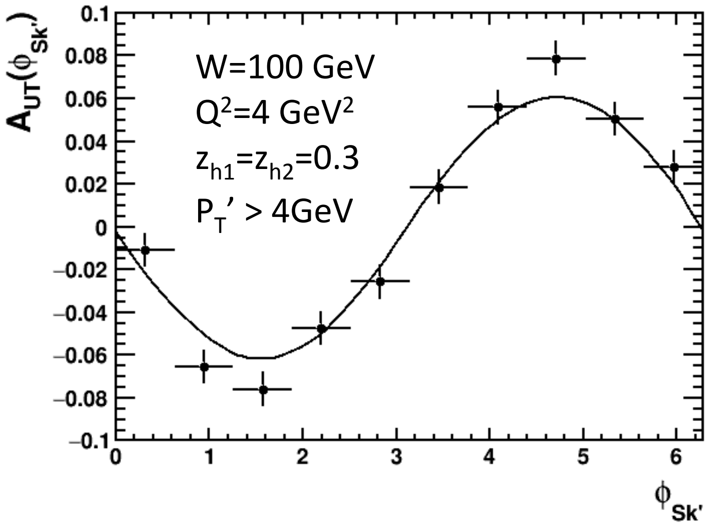
Weighting strategy vs numerical estimation

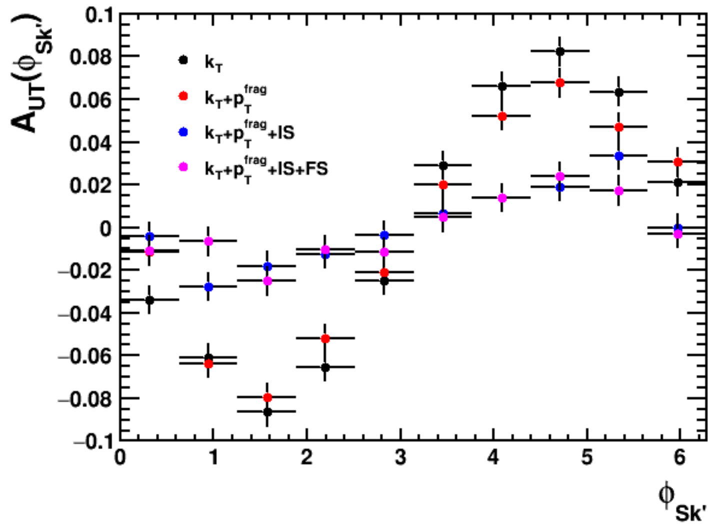
A_{UT} can be evaluated with the weighting based on input Sivers function

$$A_i = \frac{1}{N_i}\sum_{k=1}^{N_i} w_k$$

$$w_k = \frac{\Delta^N f_{a/p^\uparrow}(x, k_\perp)}{2 f_{a/p}(x, k_\perp)}$$

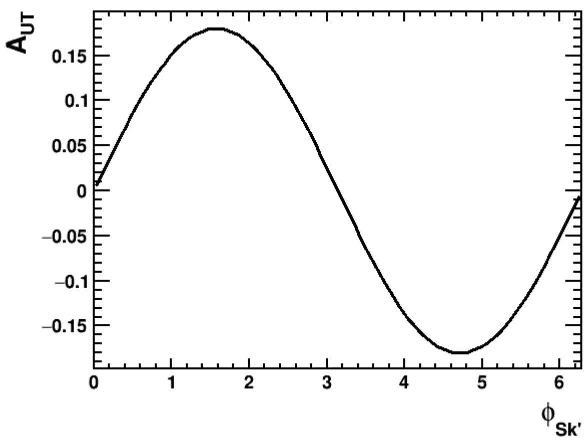
- Weighted results agree with the numerical estimations.
- Initial state parton shower suppresses the azimuthal asymmetry significantly.



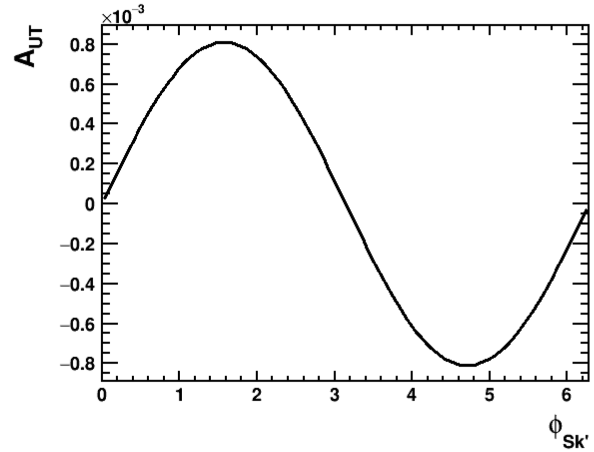


Estimates for the SSA in different processes

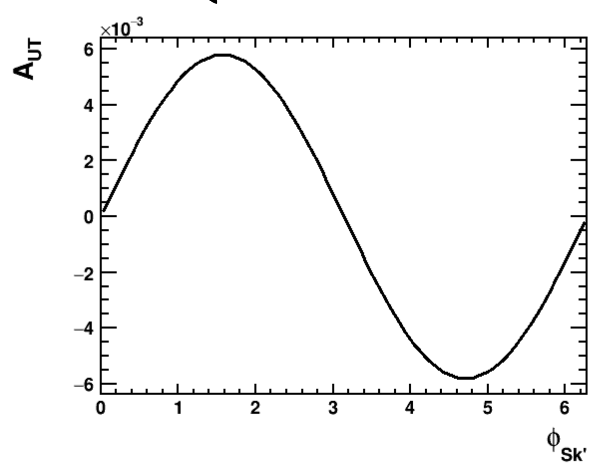
PGF postivity



PGF SIDIS1



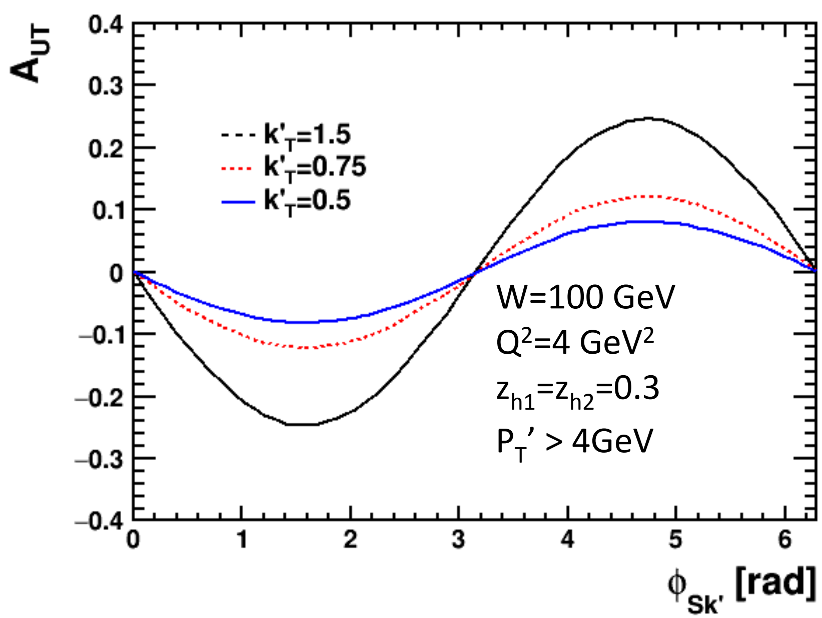
QCDC SIDIS1



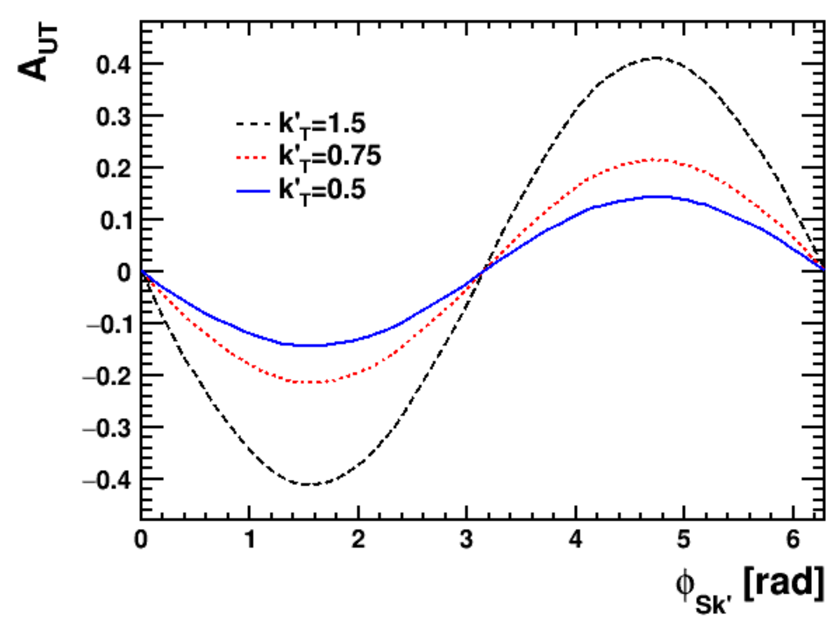
Event sample summary:
ep 20x250 GeV
0.01<y<0.95
$1<Q^2<20$ GeV^2

Numerical estimation of gluon SSA with positivity bound

D^0 $\langle p_T^2 \rangle_{frag}=0.64$



Charged dihadron $\langle p_T^2 \rangle_{frag}=0.2$

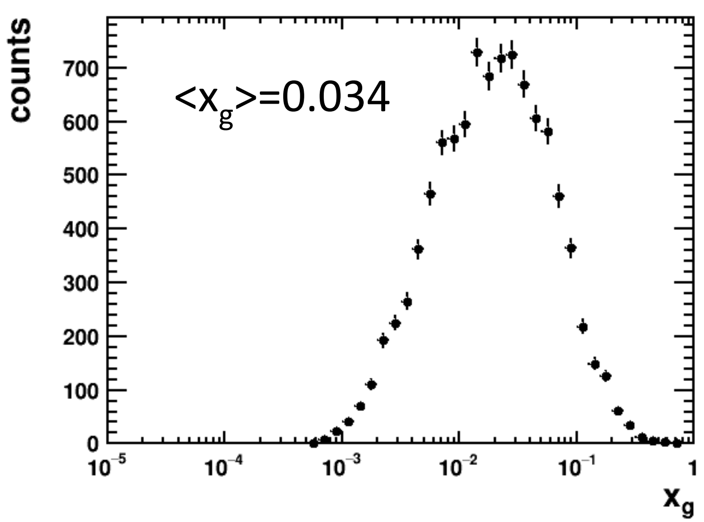


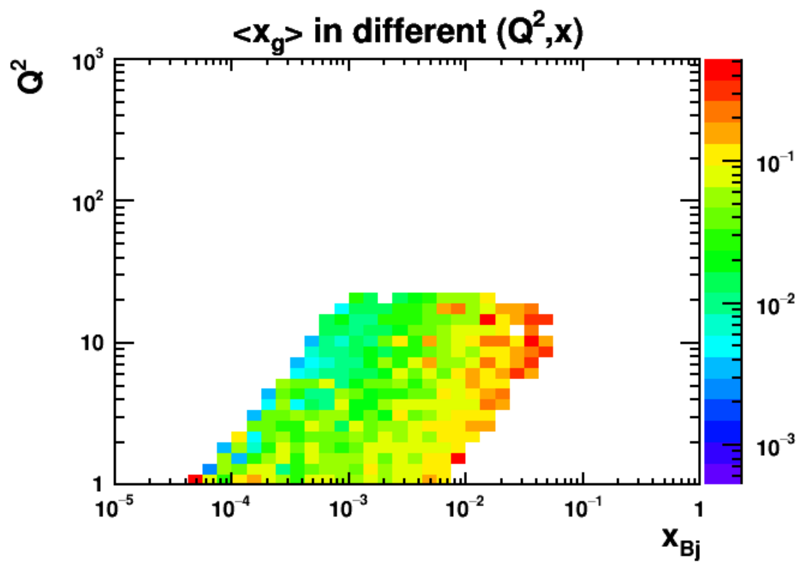
Explored gluon dynamics by the selected pairs

x_g distribution probed by the D meson pairs, overall average x_g around 10^{-2}.

$\langle x_g \rangle$ shown for every Q^2-x_{Bj} bin.

Large W ~ small x_g down to 10^{-3}.



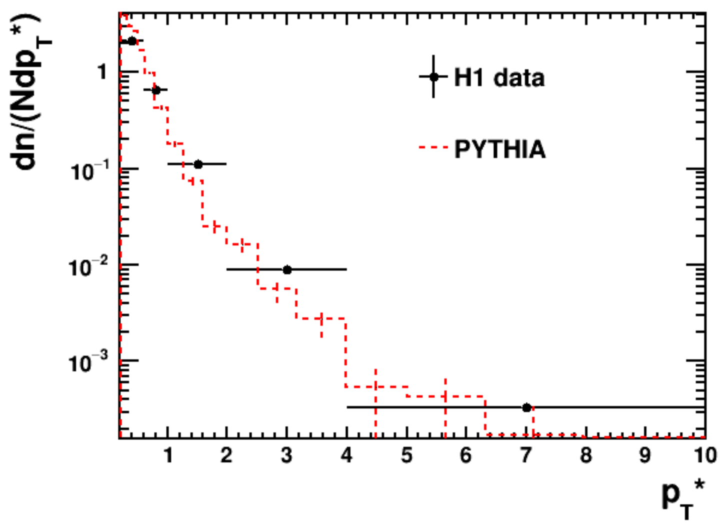


Confronting simulation with Data

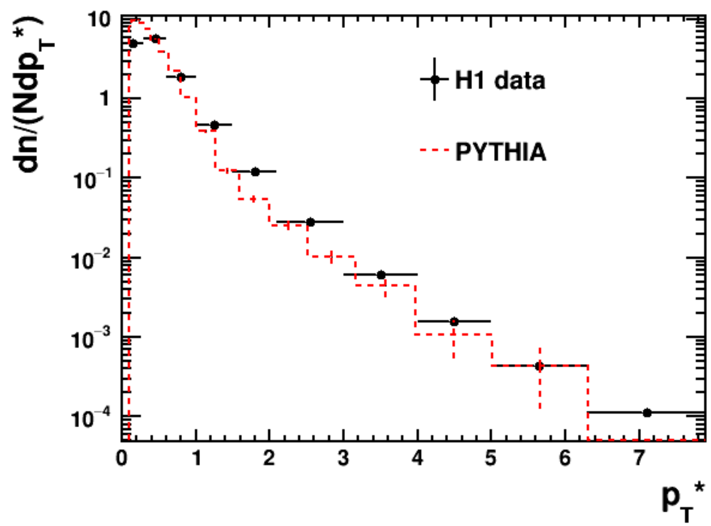
Comparing with charged hadron density measurements from HERA

Kinematics:
ep 27.6 GeV x 920 GeV
$5<Q^2<10$, $0.0005<x_{Bj}<0.002$
p_T^*, η^* defined in gamma-hadron center of mass frame

$0<\eta^*<1.5$



$1.5<\eta^*<5$



Data from EPJC 73, 2406 (2013)

H1 charged particle density data reasonably described by simulations.

Projections on the SSA with K^+K^- pairs

Kinematic cuts:
ep 20x250 GeV
$0.01<y<0.95$
$1<Q^2<20$ GeV^2
$p_T>1.7$ GeV, $z_h>0.1$, $|\eta|<3.5$
Back-to-back limit: $k_T' < 0.7P_T'$
$\sigma_{K^+K^-}=1.6\times10^{-2}$ nb
$<x_g>=0.05$

SIDIS1 Set

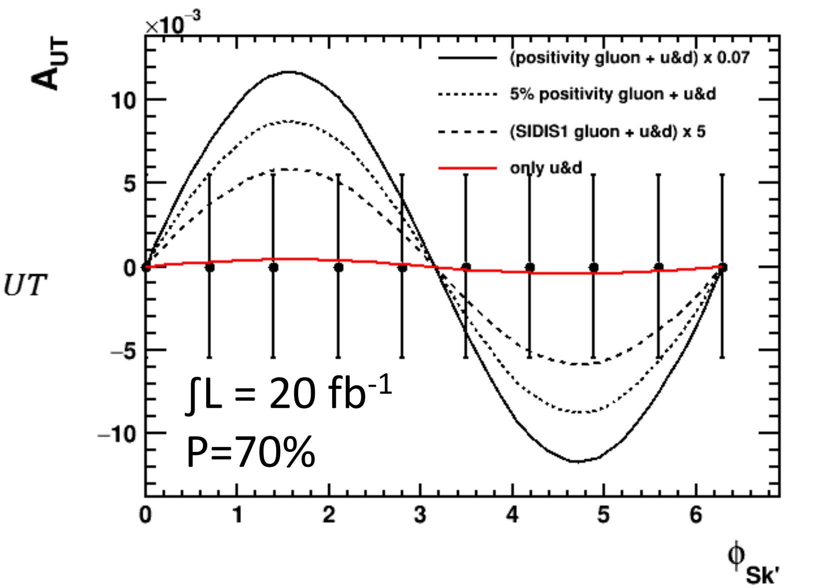
$$N_g = 0.65, \alpha_g = 2.8, \beta_g = 2.8, M_g^2 = 0.43\text{GeV}^2$$

Quark Sivers parameters (Anselmino et al.)

$$N_u = 0.4, \alpha_u = 0.35, \beta_u = 2.6,$$
$$N_d = -0.94, \alpha_d = 0.44, \beta_d = 0.9,$$
$$M_u^2 = M_d^2 = 0.19\text{GeV}^2$$

$$A(\phi_{Sk}) = R^{SIG}A^{SIG}(\phi_{Sk}) + R^{BG}A^{BG}(\phi_{Sk})$$

- Resolution power down to 5% positivity bound.
- PGF events accounting for 92.7%.
- Integrated Luminosity: 20 fb^{-1} delivers $\delta A_{UT} \approx 5.5\times10^{-3}$



Difference between black and red shows the effect of gluon Sivers